Nuclear Energy's Future Notes

This presentation addresses the evolution of nuclear reactors, advanced reactor concepts, and the prospects for nuclear fusion.

Slide 2 – nuclear reactor evolution graphic

- graphic shows evolution of nuclear power reactors beginning with post-World War II prototype reactors
- progress of nuclear power in U.S. stymied since 1970s by
  - — unwillingness of industry to adopt standardized nuclear plant designs
  - — over-regulation of industry due to use of flawed LNT dose-response model
  - — unwillingness of Nuclear Regulatory Commission to revise excessive nuclear plant licensing standards, especially for advanced reactor designs
  - — antinuclear politics regarding nuclear waste (i.e., long-term storage, nuclear weapons proliferation)

Slide 7 – Westinghouse AP-1000 plant

- design objective of AP-1000 to be less expensive to build than other Generation III reactor designs by decreasing number of components, including pipes, wires, and valves
- passive systems for reactor coolant system (RCS) decay heat removal and safety injection
- passive containment building heat removal system

Slide 8 – Generation II vs Generation III+ reactor safety

- primary objective of Generation II nuclear power plant designs was to safely generate electricity
- in response to question of what could go wrong, safety measures added to plant designs, with assumption that either offsite electrical power or onsite emergency electrical power available to support operation of safety functions and systems
- possible occurrence of station blackout event (loss of all electrical power) led to incorporation of passive safety measures into advanced plant designs, requiring no external motive force for actuation or control

Slide 9 – Generation IV reactors

- Generation IV reactors designed to use fuel more efficiently, producing smaller amounts of used fuel per unit of energy produced
- increased fuel efficiency possible because of increased fuel burnup and higher reactor operating temperatures

- — increased burnup (or energy density) achieved by using higher levels of uranium enrichment – 5-19.5% enriched uranium, called high-assay low-enriched uranium (HALEU)
- — increased burnup also accomplished by using advanced materials for fuel encapsulation (e.g., tri-structural isotropic [TRISO] particle fuel)
- — many advanced, non-light water reactors will operate at higher temperatures, meaning they can generate electricity more efficiently, thereby producing less used fuel

Slide 10 – Generation IV reactor systems under development table

- include both fast and thermal reactors (fast reactor fissions occur with high-energy neutrons, thermal reactor fissions with low-energy neutrons)
- use water, helium, molten salt, and liquid metals for reactor cooling
- use U-238, uranium fluoride salt, uranium oxide, and mixed oxide fuels
- intended use for electricity and/or hydrogen generation

Slide 11 – gas-cooled fast reactor graphic

- helium-cooled system with very high reactor outlet temperature
- can be fueled with U-238 and Pu-239 from used light-water reactor fuel and designed with passive safety features
- helium reactor coolant also working fluid for Brayton power cycle; helium doesn't get activated by neutron flux

Slide 12 – lead-cooled fast reactor graphic

- reactor cooled with liquid lead
- extremely high boiling point of lead allows reactor operation at or near atmospheric pressure
- molten lead does not react with air or water
- high density of lead provides good shielding against gamma-rays
- can be fueled with U-238 and Pu-239 from used light-water reactor fuel
- heat exchangers integral with reactor vessel
- power cycle working fluid shown in graphic is CO_2 (Brayton cycle), but water/steam (Rankine cycle) can also be used
- lead coolant must be kept in liquid state by heating during reactor shutdown
- lead coolant is opaque and corrosive, presenting operating and maintenance challenges

Slide 13 – molten salt reactor graphic

- MSRs fall into two classes
  - — salt-cooled reactors, in which core contains solid fuel and liquid salt coolant

  - salt-fueled reactors, in which nuclear fuel dissolved within liquid salt coolant
- reactor operates at or near atmospheric pressure
- can be either fast or thermal reactor and uses natural circulation for decay heat removal
- can operate with variety of nuclear fuels
- freeze plug in graphic is passive safety feature; in unlikely event of total loss of electrical power, reactor decay heat will melt freeze plug allowing salt-fuel to be drained into sub-critical emergency dump tanks
- intermediate heat exchanger separates radioactive primary molten salt coolant from power generation coolant loop preventing potential spread of radioactivity to power generation system
- power cycle working fluid shown in graphic is CO_2, but water/steam can also be used
- salt coolant must be kept in liquid state by heating during reactor shutdown
- salt coolant is opaque and corrosive, presenting operating and maintenance challenges

Slide 14 – sodium-cooled fast reactor graphic

- can be fueled with U-238 and Pu-239 from used light-water reactor fuel
- low melting point and high boiling point of sodium permits reactor operation at or near atmospheric pressure
- primary heat exchanger integral to reactor vessel
- intermediate heat exchanger separates radioactive primary sodium coolant from power generation coolant loop preventing potential spread of radioactivity to power generation system
- power cycle shown in graphic uses water/steam as working fluid
- sodium coolant must be kept in liquid state by heating during reactor shutdown
- sodium coolant is opaque and reacts violently with air and water, presenting both operating and maintenance challenges

Slide 15 – supercritical water-cooled reactor graphic

- combines decades of experience from supercritical coal plants with decades of experience from operating light water reactors
- can be fast or thermal reactor
- operates at supercritical pressure, >3000 psi, where steam and liquid water have same density
- high thermal efficiency (≈45%)
- design is once-through, direct-cycle, simplest type of cycle possible
  - water heated to critical temperature and critical pressure in reactor core where it transitions from fluid more resembling

liquid water to fluid more resembling saturated steam, but without going through distinct boiling phase transition
    - supercritical steam is working fluid for supercritical Rankine cycle
- supercritical water has excellent heat transfer properties allowing high power density, small core, and small containment structure
- higher thermal efficiency leads to better fuel economy, lighter fuel load, and decreased decay heat
- higher process heat temperatures

Slide 16 – very high temperature reactor graphic

- heats helium gas coolant to temperatures typically between 800 and 1,000 degrees Celsius, higher than temperatures used in gas-cooled fast reactors
- heat can be used by industrial furnaces to produce hydrogen, desalinate water, or refine petrochemicals
- for generating electricity, power cycle working fluid would be CO_2 (Brayton cycle)
- for process heat applications, like hydrogen production as shown in graphic, VHTR would use intermediate heat exchanger with water as secondary side working fluid to supply heat (high-temperature steam) to process application

Slide 18 – small modular reactors

- variety of SMR designs, including
    - both thermal and fast reactors
    - natural circulation reactor cooling; no need for safety-related, backup electrical systems
    - passive decay heat removal
    - primary coolant system components integral to reactor vessel (e.g., pool-type, liquid metal-cooled SMRs)
    - reactor vessel enclosed in underground containment structure
    - use of light-water reactor fuel
    - use of steam generators to provide steam as working fluid in steam turbine power cycle to generate electricity
    - use of helium or carbon dioxide as working fluid in gas turbine power cycle to generate electricity
    - process heat applications (e.g., hydrogen production or seawater desalination)

Slide 19 – SMR designs for non-electric applications graphic

- graphic illustrates variety of non-electricity-generating applications for SMRs
- graphic maps SMR types with process applications based on process temperature requirements
    - low temperature applications using water-cooled reactors include district heating and seawater desalination

- high temperature applications using very high temperature reactors include thermochemical hydrogen production, coal gasification, and blast furnace steel making

Slide 20 – some SMR concepts

- many proposed SMR designs, some further along in development than others
- table shows 6 SMR design concepts
- currently no operating SMRs in U.S.
- acronyms
  - BWR – boiling water reactor
  - PWR – pressurized water reactor
  - PRISM – Power Reactor Innovative Small Module
  - 4S – Super Safe Small & Simple
  - SG – steam generator
  - HTGR – high temperature gas-cooled reactor
  - TRISO – tri-structural isotropic micro-particle consisting of UO_2 kernel coated with 4 layers of 3 isotropic materials
  - HALEU – high assay low enriched uranium fuel (<20% enrichment)

Slide 22 – micro-reactors

- generating as little as 2 MW or as much as 50 MW of electricity, micro-reactors being designed to provide power needs for military bases, mining facilities, and communities in remote locations at lower operating cost than fossil electricity generation
- can be quickly deployed to communities affected by natural disasters
- can operate as part of electric grid, independently from electric grid, or as part of micro-grid
- variety of designs, including both thermal and fast reactors using high-assay, low-enriched uranium (HALEU) fuel

Slide 30 – Russian floating nuclear power plant graphic

- currently providing electricity and heat to Siberian city of Pevek
- ship's two pressurized water reactors generate 35 Mwe each
- heat taken from steam circuits provides district heating for town's residents

Slide 32 – nuclear fusion

- fusion research taking place since 1950s
- many companies pursuing so-far elusive goal of producing heat and generating electricity from fusion
- two main approaches for trying to accomplish fusion
  - magnetic confinement uses very powerful magnets to confine superheated plasma where atoms fuse and produce energy
  - inertial confinement uses intense set of laser beams fired at target of atoms, compressing them to point of fusing

- after 70+ years of research, timeframe for achieving scientific breakthrough for fusion as net energy source remains unknown

Slide 33 – potentially useful fusion reactions

- nearly all stable isotopes lighter than iron and nickel will fuse with some other isotope and release energy
- deuterium and tritium most attractive isotopes for energy generation as they require lowest activation energy (thus lowest temperature), while producing most energy per unit weight
- table shows deuterium-tritium fusion has lowest threshold plasma temperature and highest maximum energy gain per fusion event; hence fuel focus for most fusion machine research
- note shorthand notation for different fusion reactions
  - D-^{3}He is fusion of deuterium and helium-3
  - p-^{11}B is fusion of hydrogen (proton) and boron
  - D-T notation will hereafter be used for deuterium-tritium reaction

Slide 34 – fusion reaction rate vs plasma temperature graphic

- observe that D-T fusion has highest reaction rate at the lowest threshold ion (plasma) temperature of about 50 keV

Slide 35 – D-T fusion particle energy distribution graphic

- graphic shows D-T reaction produces 14.1 MeV neutron and 3.5 MeV helium nucleus (alpha particle)
- D-T fusion process releases roughly four times as much energy per gram of fuel as uranium-235 fission
  - U-235 fission reaction energy about 200 MeV or ≈ 0.85 MeV/g
  - D-T fusion reaction energy about 17.6 MeV or ≈ 3.5 MeV/g
  - ratio of D-T fusion specific energy to U-235 fission specific energy ≈ 4

Slide 40 – basic magnetic mirror machine

- machine uses configuration of electromagnets to create increasing density of magnetic field lines at either end of confinement volume to trap high temperature plasma
- charged particles approaching ends of confinement volume experience increasing force causing them to reverse direction and return to confinement area

Slide 41 – Z-pinch fusion graphic

- Z-pinch a type of plasma confinement system that applies very powerful electric current to plasma to generate magnetic field that squeezes plasma into fine line to create densities and temperatures that induce fusion reaction
- two main categories of Z-pinches are classical (quasi-steady state configuration with ties to magnetic confinement fusion) and pulsed (imploding configuration with ties to inertial confinement fusion)

- about a dozen experimental Z-pinch machines still used for fusion research
- PPML – University of Michigan Plasma, Pulsed Power, and Microwave Laboratory
- MAIZE – Michigan Accelerator for Inductive Z-Pinch Experiments

Slide 42 – magnetic fields in a Tokamak graphic

- as illustrated in graphic, multiple magnetic fields confine plasma inside doughnut-shaped vacuum chamber (torus), creating pressure and temperature conditions for self-sustaining fusion reaction
- toroidal field coils, running long way around chamber, squeeze plasma horizontally, producing magnetic field to prevent plasma particles from interacting with torus structure
- central solenoid creates second magnetic field running short way around chamber to squeeze plasma vertically, inducing majority of magnetic flux needed to initiate plasma reaction, generate plasma current, and maintain current during burn time
- outer poloidal field coils, arranged either symmetrically or asymmetrically relative to Tokamak equator, further shape plasma to achieve stable configuration
- Tokamak reactors aim to keep plasma continuously burning for prolonged periods of time, but despite edging ever closer have yet to create net energy gain from plasmas

Slide 43 – Joint European Torus reactor graphic

- currently largest operating Tokamak in world
- sole currently operating magnetically confined fusion device with DT capabilities
- peak fusion power about 16 megawatts
- peak fusion energy gain factor (Q) about 0.7 achieved in 1997
  - Q = 1 is scientific breakeven; that is, power released from fusion reaction equals power required to initiate fusion reaction.

Slide 44 – International Thermonuclear Experimental Reactor graphic

- cut-away view of ITER Tokamak, world's largest magnetic confinement plasma physics experiment being constructed in southern France
- 35 nations collaborating to build and operate ITER, most complex machine ever designed, to prove that fusion is viable source of large-scale, safe, and environmentally friendly energy for planet
- multi-decade, multi-billion-dollar project expected to have first plasma in 2030s
- described as most expensive science experiment of all time, most complicated engineering project in human history, and one of most ambitious human collaborations since

development of International Space Station and Large Hadron Collider
- note 2-meter-tall person standing by machine at bottom of figure

Slide 45 – Stellarator graphic
- Stellarator toroidal design differs from Tokamak toroidal design by using complicated system of magnetic coils instead of current to contain plasma
- Stellarator requires less injected power to sustain plasma, has greater design flexibility, and allows for simplification of some aspects of plasma control than Tokamak
- 2014 revelation for incorporating rare-earth permanent magnets makes for simpler design and construction

Slide 46 – inertial confinement fusion concept graphic
- inertial confinement process initiates nuclear fusion reactions by compressing and heating targets typically containing deuterium and tritium
- focusing simultaneous laser beams on fusion target one method of creating necessary pressure and temperature conditions to initiate fusion reactions
- laser beams rapidly heat surface of fusion target forming surrounding plasma envelope
- fuel compressed by rocket-like blowoff of hot surface material
- fuel core reaches 20 times density of lead and ignites at 100 million degrees Celsius
- thermonuclear burn spreads rapidly through compressed fuel, yielding many times input energy
- National Ignition Facility at Lawrence Livermore National Laboratory uses 192 laser beams to initiate fusion in deuterium-tritium target

Slide 47 – principle of inertial confinement
- to achieve continuous energy output from inertial confinement fusion devices, following processes must occur very rapidly
  — input energy source must be rapidly cycled on and off (or “recharged”)
  — potentially reaction-quenching matter created from fusion reactions must be removed between pulses
  — target must be rapidly replaced
- frozen D-T targets difficult to make and each requires days to manufacture
- inertial confinement fusion plant would need about million targets daily to produce continuous heat output

Slide 49 – laser-driven inertial confinement graphic (cont.)
- graphic illustrates laser beams initiating fusion in deuterium-tritium target

Slide 50 – National Ignition Facility graphic

- located at Lawrence Livermore National Laboratory in Livermore, California
- like ITER Tokamak, NIF is very complex machine
- inertial confinement systems generate bursts of energy by quickly burning one tiny chunk of fuel after another
  - fuel comes in form of discrete pellets, and scientists have yet to figure out how to replace them quickly enough to maintain reaction for longer than tiniest fraction of a second
- In December 2022 NIF achieved energy gain factor (Q) of about 1.5
  - energy required to charge NIF lasers about 145 times energy delivered by lasers to target pellet, so still have long way to go to achieve engineering breakeven (Q = 50)

Slide 51 – colliding beam fusion graphic

- in plasma accelerator, two plasmas formed at opposite ends of vacuum chamber
- magnets contain and accelerate plasmas toward smaller space at center of machine, generating temperature and pressure required for pulsed fusion reaction to occur
- several problems limit consideration as serious fusion power candidate, such as
  - low ion collision rate (scatter more likely than fusion)
  - equilibrium and confinement issues (little time to interact before beams fly apart)
  - space charge effects causing beams to diverge
  - beam dynamics and synchronization

Slide 52 – assessing fusion energy success

- fusion can only occur when proper plasma pressure, temperature, and density conditions achieved
- self-sustaining reaction within plasma can only be obtained if energy from fusion reactions sufficient to maintain necessary pressure, temperature, and density conditions once achieved
- since generating electricity requires extracting energy from fusion machine, fusion reaction energy must then greatly exceed that required to maintain self-sustaining reaction

Slide 59 – functional diagram of laser fusion power plant

- as shown in graphic, parasitic power consumption sources for inertial confinement fusion systems include
  - fusion pellet injection system
  - laser pulsing system
  - tritium scavenging and reinjection system
  - lithium blanket heat removal system

- not shown in graphic is cryogenic system needed for D-T pellet production

Slide 60 – functional diagram of Tokamak fusion power plant

- as shown in graphic, parasitic power consumption sources for magnetic confinement fusion systems include
  — tritium scavenging and reinjection system
  — lithium blanket heat removal system
  — lithium “breeding” blanket replenishment
- not shown in graphic is cryogenic system required for maintaining low temperature of superconducting magnets

Supplemental Information

Slide 62 – AP-1000 passive heat removal systems graphic

- design objective of AP-1000 to be less expensive to build than other Generation III reactor designs by decreasing number of components, including pipes, wires, and valves
- passive reactor coolant system (RCS) decay heat removal accomplished using natural circulation heat exchanger connected to reactor coolant system
- passive RCS safety injection utilizes nitrogen-pressurized accumulators, a gravity-drain in-containment refueling water storage tank, and natural circulation and gravity-drain core makeup tanks to maintain RCS inventory following breach of RCS
- passive containment cooling accomplished by releasing water from tank located above steel containment vessel, which flows by gravity to top of vessel where it evaporates to remove heat from inside vessel
  — removing heat from containment vessel condenses steam on internal vessel surfaces, thereby establishing natural recirculation cooling
- design intended to passively remove heat for 72 hours, after which gravity-drain water tank must be refilled for as long as cooling required

Slide 63 – Evolutionary Power Reactor graphic

- designed to use uranium more efficiently than older Generation II reactors
- design has
  — four independent emergency cooling systems
  — extra container and cooling area if molten core manages to escape reactor vessel
  — two-layer concrete containment wall

Slides 64, 65, 66 – Economic Simplified BWR graphic

- ESBWR uses natural circulation reactor core cooling

- ESBWR's passive safety systems include combination of three systems that allow for efficient transfer of decay heat from reactor to pools of water
  - Isolation Condenser System
  - Gravity Driven Cooling System
  - Passive Containment Cooling System
- systems use natural circulation to transfer decay heat outside containment structure while maintaining water levels inside reactor, keeping nuclear fuel submerged in water and adequately cooled
- both ICS and PCCS heat exchangers submerged in pool of water large enough to provide 72 hours of reactor decay heat removal capability
- being outside containment structure, pools can easily be refilled for as long as cooling required